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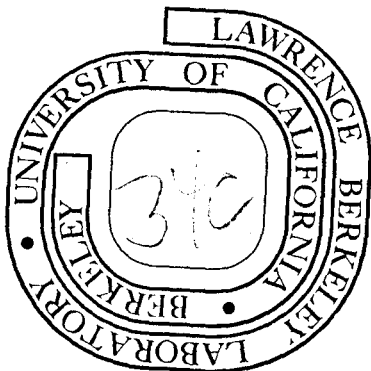
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ANGULAR-MOMENTUM EFFECTS ON CONTINUUM GAMMA RAYS

FOLLOWING HEAVY-ION REACTIONS\*

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Abstract:

The average number of continuum gamma rays above 0.6 MeV has been measured for each of several final products in the  $p+^{165}\text{Ho}$ ,  $^{16}\text{O}+^{150}\text{Sm}$  and  $^{84}\text{Kr}+^{82}\text{Se}$  reactions. This number ranges from 2 to 20 and is shown to correlate mainly with the average angular momentum leading to each product.

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The gamma-ray spectra following heavy-ion (HI, xn $\gamma$ ) reactions have two main features: discrete lines from heavily populated low-lying levels of the final product nuclei, and a continuum which presumably represents all the higher transitions, none of which has sufficient population to be resolved with present techniques. Most recent work has focused on the discrete lines, producing systematic information on the low-lying high-spin ( $\sqrt{20}\hbar$ ) states of nuclei. A few attempts have been made to study the continuum region. Mollenauer<sup>1</sup> studied ( $\alpha$ , xn $\gamma$ ) and ( $^{12}\text{C}$ , xn $\gamma$ ) reactions without specifying the outgoing reaction channel. He measured the average number of continuum gamma rays,  $\bar{N}_\gamma$ , their average energy and their angular distribution. Sunyar<sup>2</sup> has

reported some preliminary results on  $\bar{N}_\gamma$  for the  $^{150}\text{Nd} (^{13}\text{C}, 5n\gamma) ^{158}\text{Dy}$  reaction. The present work, using p,  $^{16}\text{O}$ , and  $^{84}\text{Kr}$  projectiles, shows that large variations occur in the number of gamma rays in the continuum region depending mainly on the outgoing channel, and that this variation may be understood in terms of a simple model.

In our work it was essential to specify the reaction channel because many channels occur simultaneously in the reactions and a composite continuum of gamma rays would be difficult to interpret. Thus we measured the continuum in coincidence with known discrete transitions that specified particular channels, as was done by Sunyar<sup>2</sup>. For the discrete lines we used a 40cc Ge(Li) detector at an angle of  $90^\circ$  to the incident beam direction and about 5 cm from the target. The continuum gamma-rays were detected in a 7.5 x 7.5 cm NaI crystal, 15 cm from the target, and at angles of  $0^\circ$ ,  $45^\circ$ , and  $90^\circ$ . An absorber, consisting of 0.32 cm Pb and 0.32 cm Cu, was placed in front of the NaI detector, resulting in an overall detection efficiency which is very nearly constant for any gamma ray above 0.5 MeV. Since there are known discrete lines in the spectra of interest up to about 0.6 MeV, and since there are not likely to be many continuum gamma rays below this energy,<sup>1,2</sup> we took 0.6 MeV as the lower limit for measurements of the continuum. The detection probability for 1.1, 1.4, and 2.8 MeV gamma rays in the coincidence arrangement was found to be the same within about 20% and equal to 0.43%. Thus, even for multiplicities as high as 20, the probability of two gamma rays being detected simultaneously was less than 10% and represented a small correction. The arrangement was further tested with a  $^{252}\text{Cf}$  fission source, using fission fragments as the coincidence triggers, and agreement with previous results<sup>3</sup> for the number of gamma rays per fission was obtained. In these calibrations,

as well as during the in-beam experiments, a background spectrum was taken with a 5 cm thick Pb cone between the NaI detector and the source (target). We have shown that a simple subtraction of the spectrum with Pb cone from that with no cone is very unlikely to cause an error in  $\bar{N}_\gamma$  exceeding 10%.

Beams of 347 MeV  $^{84}\text{Kr}$  provided by the Berkeley SuperHILAC were used to bombard targets of  $^{82}\text{Se}$  ( $1.3 \text{ mg/cm}^2$ ) enriched to 97%. This produced the compound nucleus  $^{166}\text{Yb}$ , and various discrete lines in the final nuclei  $^{163}\text{Yb}(3n)$ ,  $^{162}\text{Yb}(4n)$ , and  $^{161}\text{Yb}(5n)$  could be used as coincidence gates. A target of 99% enriched  $^{150}\text{Sm}$  ( $1.4 \text{ mg/cm}^2$ ) was also bombarded at the Berkeley 88-inch cyclotron with 88 MeV  $^{16}\text{O}$  to produce the same compound nucleus and products. Both targets were evaporated onto Pb backings about 25  $\mu\text{m}$  thick, which stopped the beam and recoiling nuclei with no appreciable background. We also bombarded a  $^{165}\text{Ho}$  target ( $220 \text{ mg/cm}^2$ ) with 25 MeV protons at the cyclotron in order to produce the compound nucleus  $^{166}\text{Er}$ , and product nuclei  $^{163}\text{Er}(3n)$  and  $^{164}\text{Er}(2n)$ . The average numbers of gamma rays,  $\bar{N}_\gamma$ , associated with each discrete line are given in Table I. The uncertainty attached to each  $\bar{N}_\gamma$  value is estimated to be  $\pm 20\%$ , except for the 232 keV line in the  $^{84}\text{Kr} + ^{82}\text{Se}$  data. This line appeared broad both in the singles and coincident spectra, and thus the uncertainty toward lower values has been doubled to 40%.

The variations of  $\bar{N}_\gamma$  in Table I are more than a factor of 10 overall, and nearly a factor of 3 in various  $^{16}\text{O} + ^{150}\text{Sm}$  reactions alone. Such large variations are not likely to be caused simply by the difference in excitation energy resulting from different numbers of neutrons evaporated. This is shown by the  $p + ^{165}\text{Ho}$  reaction, where a difference of one neutron causes a change of less than 2 gamma rays. It seems more likely that these large variations in  $\bar{N}_\gamma$  result from angular-momentum effects. This can be tested by application

of a simple semi-classical model<sup>4</sup>. We picked a compound nucleus as neutron rich as possible in order to be able to neglect charged-particle competition, and indeed, the (HI, $\alpha$ nxnY) products that could be detected in our spectra had individual cross sections less than 10 mb. The number of neutrons emitted from a compound system depends on the energy available, which is roughly the difference between the excitation energy and the minimum energy  $E_\ell$  required to carry the angular momentum  $\ell\hbar$  of the system. Since an evaporated neutron cannot change  $\ell$  by more than 1 or 2 units, the energy  $E_\ell$  must be left in the residual nucleus. If for example,  $\ell$  is such that  $E_\ell$  is equal to the sum,  $E_n$ , of the neutron binding and kinetic energies, then it is apparent that one fewer neutron can be emitted than would be the case for  $\ell = 0$  ( $E_0 = 0$ ). We can estimate that  $E_\ell \approx \hbar^2 \ell^2 / 2\mathcal{I}$ , where  $\mathcal{I}$  is a moment of inertia near the rigid-body value. Since  $E_n$  is about 10 MeV for the nuclei considered here, and  $\frac{\hbar^2}{2\mathcal{I}}$  is approximately 9 keV, this gives  $\Delta(\ell^2)/\Delta x = 1100$  ( $x$  is the number of neutrons emitted). Thus if a large amount of angular momentum is brought into a compound nucleus in this region, the total cross section will be divided into "bins", having a width  $\Delta(\ell^2) = 1100$ , each of which corresponds to a particular number of neutrons being evaporated. For example, if a bin starts at  $\ell = 0$ , it can hold all angular momenta up to 33, and the bin starting at  $\ell = 33$  corresponds to the evaporation of one less neutron. It is important to note that at a given bombarding energy the maximum cross section for each bin is approximately constant. Using a relation given previously<sup>5</sup>;  $\ell_{\text{upper}}^2 = 1.5\mu E_{\text{CM}}$ , where  $\sigma$  is in barns,  $\mu$  is the reduced mass in mass units, and  $E_{\text{CM}}$  is the center-of-mass energy in MeV.

$$\frac{\Delta\sigma}{\Delta x} = \frac{[\Delta(\ell^2)/\Delta x]}{1.5 \mu E_{\text{CM}}} \approx \frac{740}{\mu E_{\text{CM}}} \quad (1)$$

For our  $^{16}_0 + ^{150}\text{Sm}$  case, with  $\mu = 14.5$  and  $\bar{E}_{\text{CM}} = 78$ , Eq. (1) gives  $\Delta\sigma = 650$  mb, compared with our measured  $\Delta\sigma$  for the 4n reaction of  $540 \pm 100$  mb. For the  $^{84}\text{Kr} + ^{82}\text{Se}$  case, Eq. (1) gives  $\Delta\sigma = 110$  mb, compared with our measured 4n cross section of  $105 \pm 25$  mb. For protons, the calculated  $\Delta\sigma$  is around 30 b, indicating a bin size much larger than the reaction cross section. Thus Eq. (1) seems reasonably well borne out in our cases.

Some of the expectations derived from this simple model for our three projectile-target systems are illustrated in Fig. 1. First the yrast, or lowest-energy, states for each  $\ell$  are plotted using the  $\frac{\hbar^2}{2\mathcal{I}}$  value given above. For the  $^{16}_0 + ^{152}\text{Sm}$  case we take the 4n cross section of 540 mb to represent a "full" bin. The measured 5n cross section then represents 0.22 of a bin or a  $\Delta(\ell^2)$  of 240, and the 3n cross section represents 0.09 of a bin or  $\Delta(\ell^2) = 100$ . Thus the 5n-4n boundary can be located at  $\ell^2 = 240$ , the 4n-3n boundary at  $\ell^2 = 1340$ , and the upper limit of the 3n reaction at  $\ell^2 = 1440$ . This indicates  $\ell_{\text{max}}$  for this reaction to be 38, in accord with the estimate:

$$\ell_{\text{max}} = 0.219 R[\mu(E_{\text{CM}} - E_{\text{CB}})]^{1/2} \quad (2)$$

where  $E_{\text{CB}}$  is the Coulomb barrier energy in MeV and  $R$  is the sum of the nuclear radii in fm. For the  $^{84}\text{Kr} + ^{82}\text{Se}$  case, we again take our 4n cross section as a full bin, and find 0.27 and 0.65 bins for the 5n and 3n reactions, respectively. This makes the 5n-4n boundary at  $\ell^2 = 304$ , the 4n-3n boundary at  $\ell^2 = 1410$ , and the upper limit of the 3n reaction at  $\ell^2 = 2140$ . This indicates an  $\ell_{\text{max}}$  of 46, whereas Eq. (2) gives  $\ell_{\text{max}} = 79$ . At first this might seem surprising since the 3n is not a full bin according to our measurements and we find the 2n cross section to be only  $\sim 5$  mb. However, it is well known that above a certain angular momentum the compound nucleus fissions<sup>6</sup> or does not form<sup>7</sup>, and the above value



of  $\sim 50\hbar$  represents an experimental estimate of that angular momentum. For the  $p + {}^{165}\text{Ho}$  reaction, Eq. (2) gives 10, so that essentially no angular-momentum effects should occur.

For each full or partial bin in Fig. 1, an rms value of  $\ell$  can be estimated. These are 11, 28, and 37 for the 5n, 4n, and 3n reactions in the  ${}^{16}\text{O} + {}^{150}\text{Sm}$  case; 12, 29, and 42 for the  ${}^{84}\text{Kr} + {}^{82}\text{Se}$  case; and 6 for the  $p + {}^{165}\text{Ho}$  case. To test whether the  $\bar{N}_\gamma$  values from Table I correlate with these  $\ell_{\text{rms}}$  values, we have plotted these quantities against each other in Fig. 2. For the  $p + {}^{165}\text{Ho}$  case, we took an average (weighted by the cross sections) for the 2n and 3n reactions of  $\bar{N}_\gamma = 3$ . It is quite apparent that a correlation exists in Fig. 2, although the relationship is not so good as to completely exclude the possibility of some other effects. For example there is some suggestion that the  ${}^{84}\text{Kr} + {}^{82}\text{Se}$  reaction produces slightly more gamma rays than does the  ${}^{16}\text{O} + {}^{150}\text{Sm}$  reaction. Nevertheless, we conclude that most of the variation of  $\bar{N}_\gamma$  is due to variation of the input angular momentum. The correlation in Fig. 2 also supports the ideas embodied in Fig. 1, and indicates that the lines separating the different bins cannot be too fuzzy.

It is also interesting to consider whether there are enough gamma rays to carry off the rms  $\ell$ -values obtained from Fig. 1. Figure 2 shows that an input angular momentum of  $30\hbar$  gives about 10 gamma rays. Since a multipolarity higher than E2 is not likely, this accounts for a maximum of  $20\hbar$ . However, the 4n reactions from both  ${}^{16}\text{O} + {}^{150}\text{Sm}$  and  ${}^{84}\text{Kr} + {}^{82}\text{Se}$  have at least 5 discrete gamma rays below 0.6 MeV which are known to carry off  $10\hbar$ . In the odd-mass cases (3n and 5n reactions) even more angular momentum is carried off by the discrete lines. Thus the  $\bar{N}_\gamma$  values are consistent with the rms  $\ell$ -values

estimated from Fig. 1 provided the continuum gamma rays are predominantly of the stretched ( $I \rightarrow I-2$ ) E2 type. It is not yet clear whether the angular distributions are consistent with this requirement. The situation is somewhat relieved since the neutrons may carry off a few units of angular momentum, and there may be a few continuum gamma rays below 0.6 MeV.

We have found large variations in the number of gamma rays emitted following (HI,xn $\gamma$ ) reactions, especially for different products of the same target-projectile system. These variations have been shown to be mainly an angular momentum effect, and support a simple model which gives considerable insight into the effects of angular momentum in compound nucleus de-excitation. The question as to how much information the continuum gamma rays can give beyond these angular-momentum effects is an interesting one. Some of our preliminary results for average energies and angular distributions of the continuum gamma rays suggest that different de-excitation modes in a given product nucleus can be distinguished experimentally.

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FOOTNOTES AND REFERENCES

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†On leave from University of Oslo, Norway

‡On leave from University of Munich, Germany

‡On partial leave from Stanford University, California

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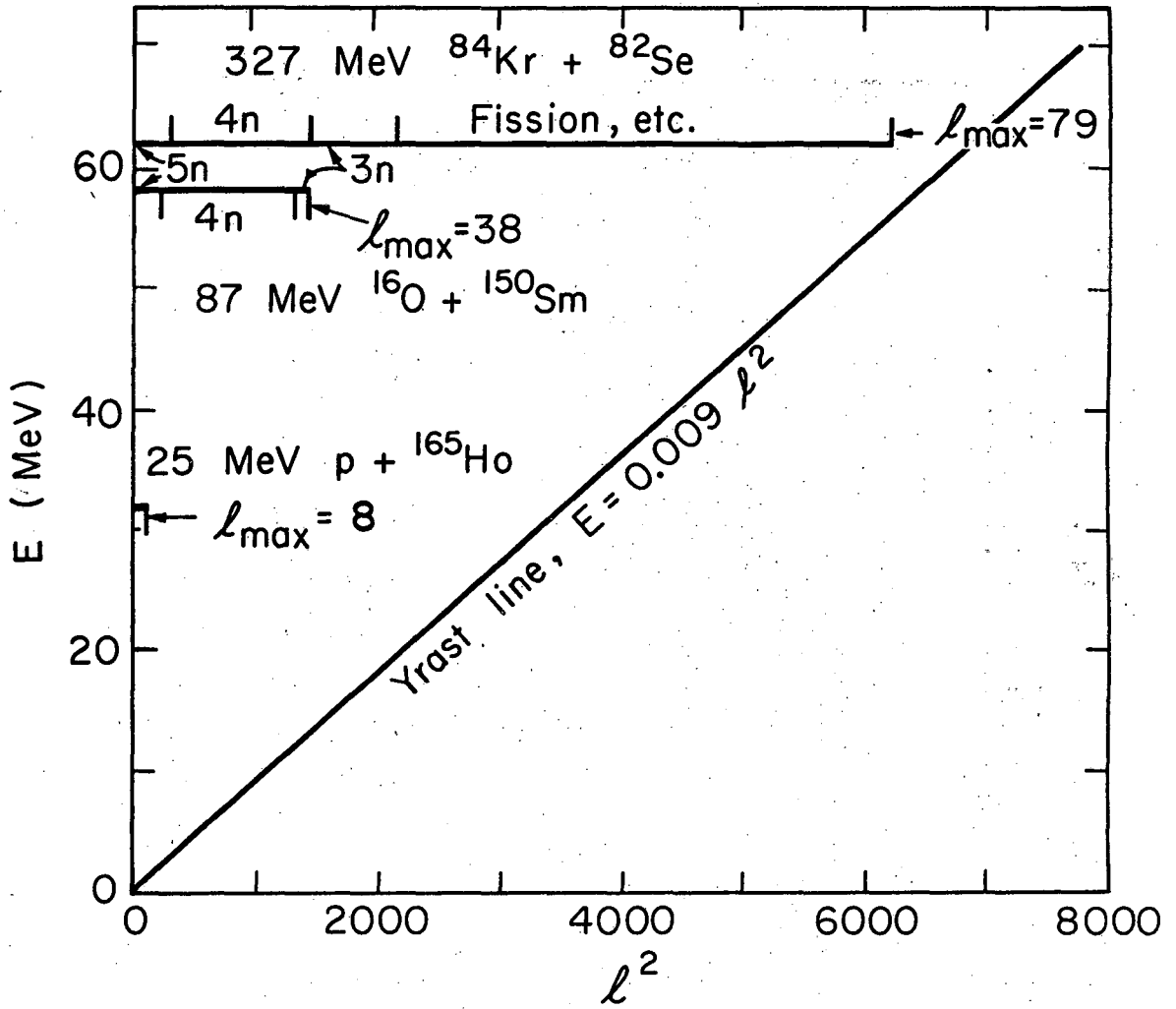
Table I. Average number of continuum gamma-rays above 0.6 MeV.

| $^{84}\text{Kr} + ^{82}\text{Se}$ |                                      |                  | $^{16}\text{O} + ^{150}\text{Sm}$ |        | $p + ^{165}\text{Ho}$                   |                  |  |
|-----------------------------------|--------------------------------------|------------------|-----------------------------------|--------|-----------------------------------------|------------------|--|
| E(kev)                            | $I_i \rightarrow I_f$                | $\bar{N}_\gamma$ | $\bar{N}_\gamma$                  | E(kev) | $I_i \rightarrow I_f$                   | $\bar{N}_\gamma$ |  |
|                                   | $^{162}\text{Yb} (4n)$               |                  |                                   |        | $^{163}\text{Er} (3n)$                  |                  |  |
| 166                               | 2→0                                  | 11               | 8                                 | 127    | (13/2 <sup>+</sup> →9/2 <sup>+</sup> )  | 1.2              |  |
| 320                               | 4→2                                  | 14               | 10                                | 165    | (15/2 <sup>+</sup> →13/2 <sup>+</sup> ) | 2.2              |  |
| 437                               | 6→4                                  | 12               | 9                                 | 171    | (13/2 <sup>-</sup> →11/2 <sup>-</sup> ) | 2.3              |  |
| 521                               | 8→6                                  | 12               | 9                                 | 190    | 9/2 <sup>-</sup> →5/7 <sup>-</sup>      | 1.3              |  |
| 579                               | 10→8                                 |                  | 9                                 | 213    | (15/2 <sup>+</sup> →11/2 <sup>+</sup> ) | 1.3              |  |
|                                   | $^{163}\text{Yb} (3n)$               |                  |                                   | 218    | (17/2 <sup>+</sup> →13/2 <sup>+</sup> ) | 1.7              |  |
| 202                               | 17/2 <sup>+</sup> →13/2 <sup>+</sup> | 20               | 14                                | 236    | 11/2 <sup>-</sup> →7/2 <sup>-</sup>     | 1.6              |  |
| 345                               | 21/2 <sup>+</sup> →17/2 <sup>+</sup> | 19               | 9                                 |        | $^{164}\text{Er} (2n)$                  |                  |  |
|                                   | $^{161}\text{Yb} (5n)$               |                  |                                   | 208    | 2→0                                     | 3.7              |  |
|                                   |                                      |                  |                                   | 314    | 4→2                                     | 3.3              |  |
| 232                               | 17/2 <sup>+</sup> →13/2 <sup>+</sup> | 10               | 5                                 | 410    | 6→4                                     | 3.2              |  |

## FIGURE CAPTIONS

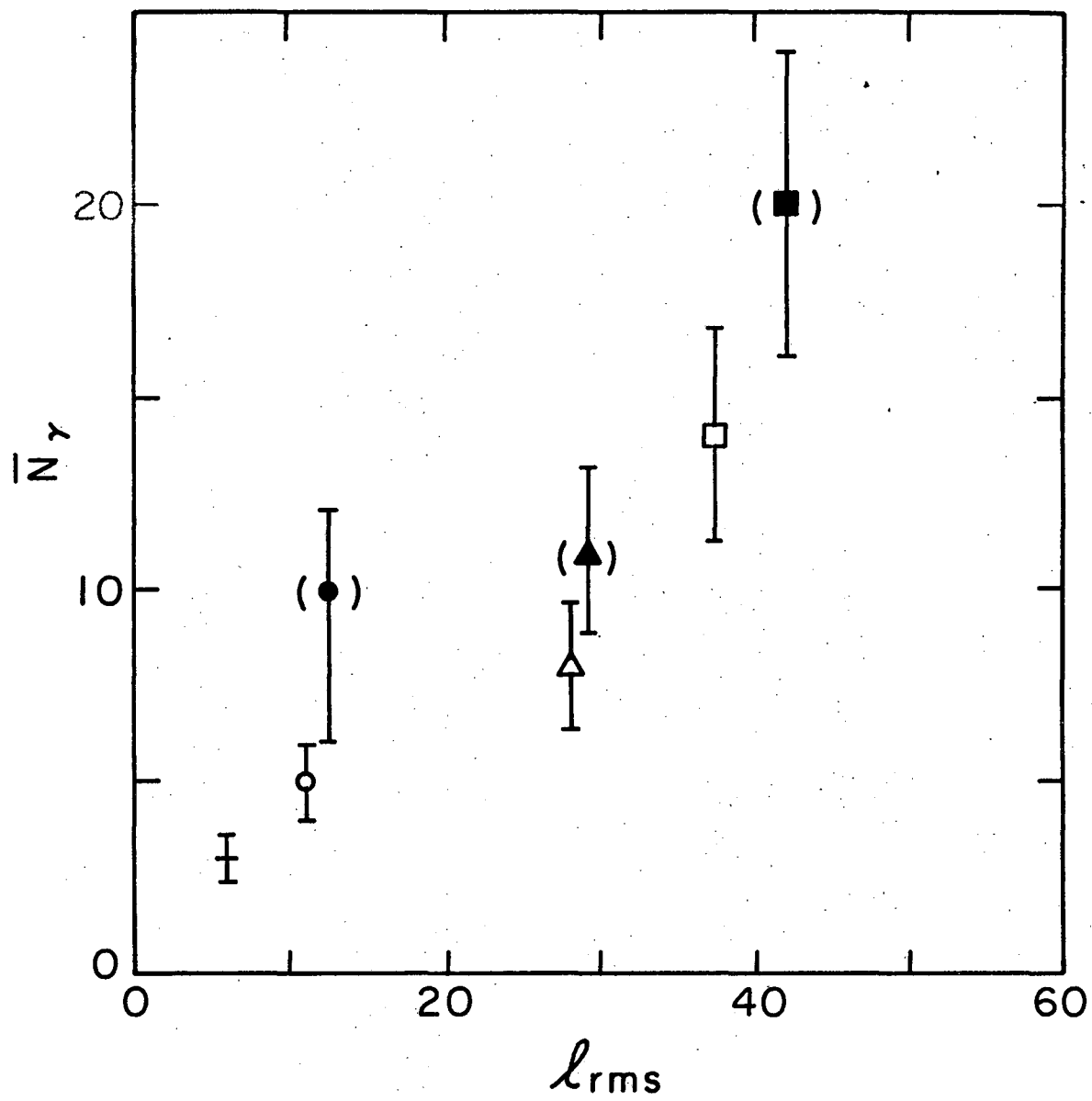
Fig. 1. A plot of excitation energy versus angular momentum squared for a nucleus having  $A \approx 160$ . The yrast line is shown, together with the excitation energies and angular-momentum ranges for the three reactions studied. The projectile energies shown have been corrected for target thickness.

Fig. 2. The average number of continuum gamma rays ( $E_\gamma > 0.6$  MeV) coincident with the lowest observed discrete transition ( $2 \rightarrow 0$  or  $17/2 \rightarrow 13/2$ ) vs. the input  $\ell_{\text{rms}}$  values estimated from Fig. 1. The cross is for the  $^{165}\text{Ho}(p, xn\gamma)^{163,4}\text{Er}$  reaction and the circles, triangles and squares are for the  $5n$ ,  $4n$ , and  $3n$  reactions from  $^{16}\text{O} + ^{150}\text{Sm}$  (open) and  $^{84}\text{Kr} + ^{82}\text{Se}$  (solid). The parentheses on the  $^{84}\text{Kr} + ^{82}\text{Se}$  data indicate that considerable uncertainty in the  $\ell_{\text{rms}}$  values is introduced by the target thickness in this case.



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Fig 1.



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Fig. 2

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